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14. ABSTRACT

This purpose of this grant focused on the optical and electronic characterization and fabrication of antimonide-based semiconductor lasers for infrared applications. Recent results with Optical Pumping Injection Cavity (OPIC) lasers includes >4 μm emission from a broadband laser and the measurement of spatial and temporal beam profiles. From August 2006 through December of 2007, the work was expanded to include the development of plasma etch processes in an Oxford Instruments 100 ICP 180 System for ZnO layers and the definition of antimonide laser structures. The laser structures were etched in a 25% BCl_3 / 75% Ar chemistry (5 sccm BCl_3 and 15 sccm argon) at 15 mTorr, 400W ICP, and 70W RIE power, with an etch rate of 300 nm/min. Epitaxial ZnO layers were plasma etched using BCl_3/SF_6 gas mixtures. Etch rates were studied as a function of gas composition, ICP coil power and RF power. The ZnO etch rate in pure BCl_3 at a pressure of 10 mTorr, RF power of 350W, and ICP power of 1000W was ~1175 Å/min (-1000V bias). The etch rate increased with increasing SF_6 percentage in the flow, and for the same conditions in pure SF_6 the etch rate was ~1350 Å/min (-820V bias).

15. SUBJECT TERMS

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Karen J. Nordheden
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AFOSR Final Performance Report, May 2009

Award No.: FA9550-04-1-0433

Title: (DEPSCOR FY04) High Efficiency, Room Temperature Mid-Infrared Semiconductor Laser Development for IR Countermeasures

Principal Investigator: Karen J. Nordheden (replacement PI for Linda Olafsen)

Institution: University of Kansas Center for Research, Inc.
2385 Irving Hill Rd.
Lawrence, KS 66045-7563

Note: This is a follow-up to the final report submitted in March 2008 which is included at the end of this report.

Revised Objectives:

There were no major changes to the overall original grant proposal objectives which included the optical and electronic characterization and fabrication of antimonide-based semiconductor lasers for infrared applications. The fabrication of the devices continued to be done at KU (Nordheden), and the optical and electronic characterization of the devices were carried out at Baylor (Olafsen, without the use of any DEPSCoR funds). The necessary fabrication equipment for photolithography, metallization, plasma etching and passivation all remained at KU. The KTEC equipment matching funds which remained unspent were used to purchase a thin film measurement system. The optical and electronic characterization equipment was moved to Baylor. Dr. Nordheden developed plasma processes for antimonide-based semiconductor etching and nitride passivation. Since the same supplies/equipment used for etching the antimonide materials could also be used for ZnO etching, we expanded the original work to include this as well.

Revised Budget:

The equipment match from the State of Kansas (KTEC) was used to purchase a thin film/index of refraction measurement system (Horiba ellipsometer) to help monitor thin films during processing (nitride and/or photoresist thicknesses, etc.). The remaining equipment funds were used to purchase a turbo pump for the RIE system and a 1000X optical microscope for process inspection.

STATUS OF EFFORT:

The status of effort section will be divided into three categories: ZnO etching results, mid-IR antimonide laser progress, and equipment installation and purchases.

ZnO etching results:

The etch studies were performed in an Oxford Instruments System 100 ICP 180. The ICP and RF substrate electrode were biased with independent power supplies both at a frequency of 13.56 MHz. The aluminum chamber was evacuated by an Alcatel turbo pump backed by a BOC Edwards iH80 dry pump. Samples were affixed with a small amount of Apiezon high vacuum grease to a 4" silicon carrier wafer and loaded into the system via a load-lock. Helium backside cooling (10 Torr) was applied to the back of the silicon carrier to ensure efficient heat transfer during etching. Gases were introduced with mass flow controllers. Single crystal epitaxial layers of ZnO grown on sapphire substrates by Nanovation were used for the etch studies. A thin layer (~1000Å) of silicon dioxide was deposited on the samples prior to masking in an Oxford Instruments 80 PECVD system (350°C, 1 Torr, 200 sccm SiH_4, 700 sccm N_2O) to protect the ZnO from the photolithography process. The thicknesses of the unmasked ZnO films and the silicon dioxide layers (on silicon monitor samples) were measured with a Horiba Jobin-Yvon UVISEL ellipsometer. The samples were then masked with 5 μm of S1818 photoresist and post-baked at 90°C for 30 seconds on a hotplate. Windows were opened in the SiO_2 using a Plasma Therm 790 RIE (30°C, 50 mTorr, 10 sccm SF_6, 10 sccm He, 75 Watts, -110V self-bias) to expose the underlying ZnO for ICP etching. An open area of one ZnO sample was remeasured with the ellipsometer after removal of the silicon dioxide to verify that the silicon dioxide etch did not remove any of the ZnO. Etch depths were measured with a Dektak surface profilometer.

The etch rate of ZnO with a composition of 50% SF_6 in BCl_3 in an Oxford Instruments 100 ICP 180 system is shown below in Figure 1. At a pressure of 15 mTorr and RF power of 200W, the etch rate increased from 300 Å/min to 400 Å/min as the ICP power was increased from 800W to 1000W (-700V bias). At a pressure of 10 mTorr, an RF power of 350W, and an ICP power of 1000W, the etch rate increased to 1230 Å/min (-865V bias). The lower pressure and higher RF power would both contribute to an increase in the ion bombardment energy.

The etch rate of ZnO at a pressure of 10 mTorr as a function of SF_6 percentage in the flow (20 sccm total) with a constant RF power of 350W and a constant ICP power of 1000W is shown in Figure 2. The ZnO etch rate increased as the percentage of SF_6 in the flow increased. In pure BCl_3, the etch rate was just under 1200 Å/min, and the rate increased to about 1350 Å/min in pure SF_6. This is comparable to the etch rate reported by H.-K. Kim, *et. al.* in a pure BCl_3 plasma under similar conditions (1280 Å/min).[1] Since fluorine is also an etch species for ZnO, it is possible that the etch rate increase with increasing SF_6 percentage may be primarily due to an increase in fluorine species.

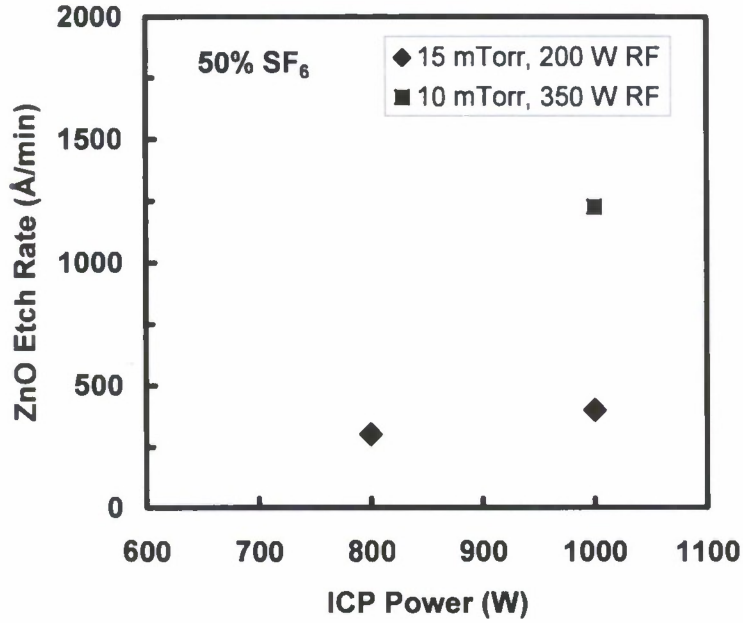

Fig. 1. ZnO etch rate as a function of ICP power with pressure and RF power as parameters (10 sccm SF_6, 10 sccm BCl_3).

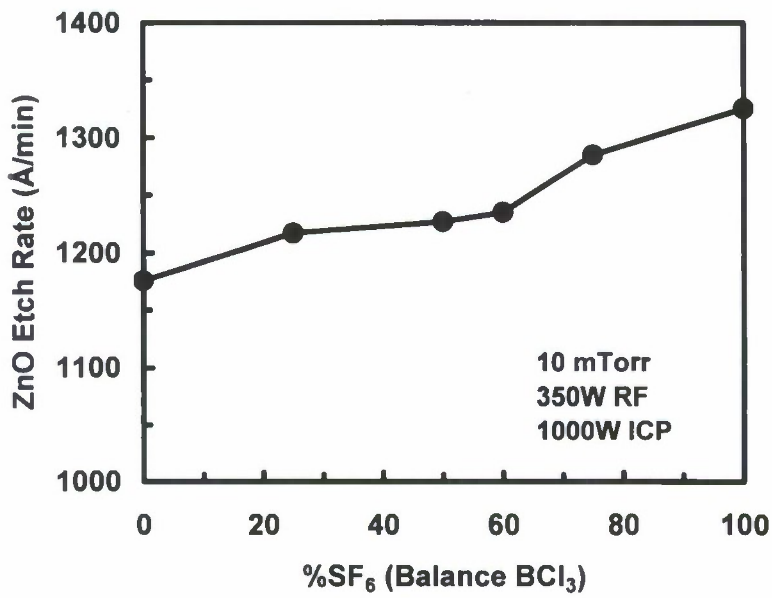

Fig. 2. Etch rate of ZnO as a function of SF_6 percentage in the flow (20 sccm, 10 mTorr, 350W RF power, 1000W ICP power).

These results (in BCl_3/SF_6) were presented at an invited talk at Photonics West in January 2009, and are to be published in the proceedings.

The results from previous work on plasma etching of ZnO in CH_4/H_2 and $BCl_3/CH_4/H_2$ gas mixtures, in a collaboration with Mark Dineen and Colin Welch at Oxford Instruments Plasma Technology, was published in the 2007 Proceedings of SPIE.

Mid-IR Antimonide laser progress:

Olafsen at Baylor University:

Investigations of Optical Pumping Injection Cavity (OPIC) lasers have continued, including measurements of a broadband OPIC laser prepared in collaboration with Naval Research Laboratory (Jerry Meyer's group). These laser materials display resonant behavior in which laser threshold pumping intensities are minimized and power conversion efficiencies are maximized by optically pumping at a wavelength resonant to the cavity surrounded by a $GaSb/AlAs_{0.08}Sb_{0.92}$ distributed Bragg reflector (Fig. 3). The successful demonstration of these materials is notable, not only for the broader resonance for maximizing efficiency and minimizing threshold, but also for the epi-side down configuration that allows for improved heat dissipation. Also important is the >4 μm emission of these materials, compared with 3 μm emission in other OPIC lasers studied.

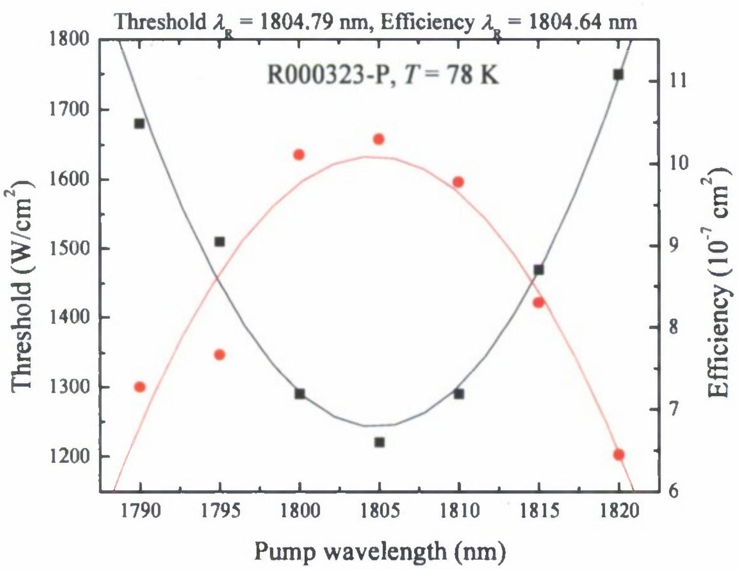

Fig. 3 Threshold intensity (black squares, left axis) and power conversion efficiency (red circles, right axis) at 78 K for a broadened OPIC laser emitting ~4 μm.

Another developing aspect of the investigation at Baylor is measurement of spatial and spatio-temporal beam profiles. Using a PV320 Infrared camera from Electrophysics (now Sofradir), we are developing techniques to image both pump laser and mid-IR semiconductor output beam profiles, as well as to image the semiconductor laser facets to pinpoint hotspots (Fig. 4). While there are other detectors for examining individually the spatial and temporal characteristics of laser light in the mid-IR, the use of a thermal camera designed to operate in the

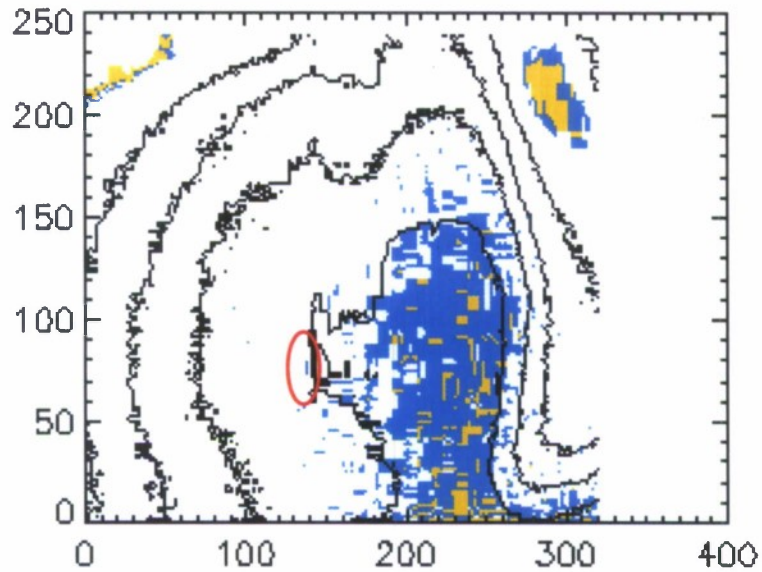

Fig. 4. Composite image taking the difference between "on" and "off" configurations for an electrically injected laser diode. The blue pixels in the circle correspond to the sample facet.

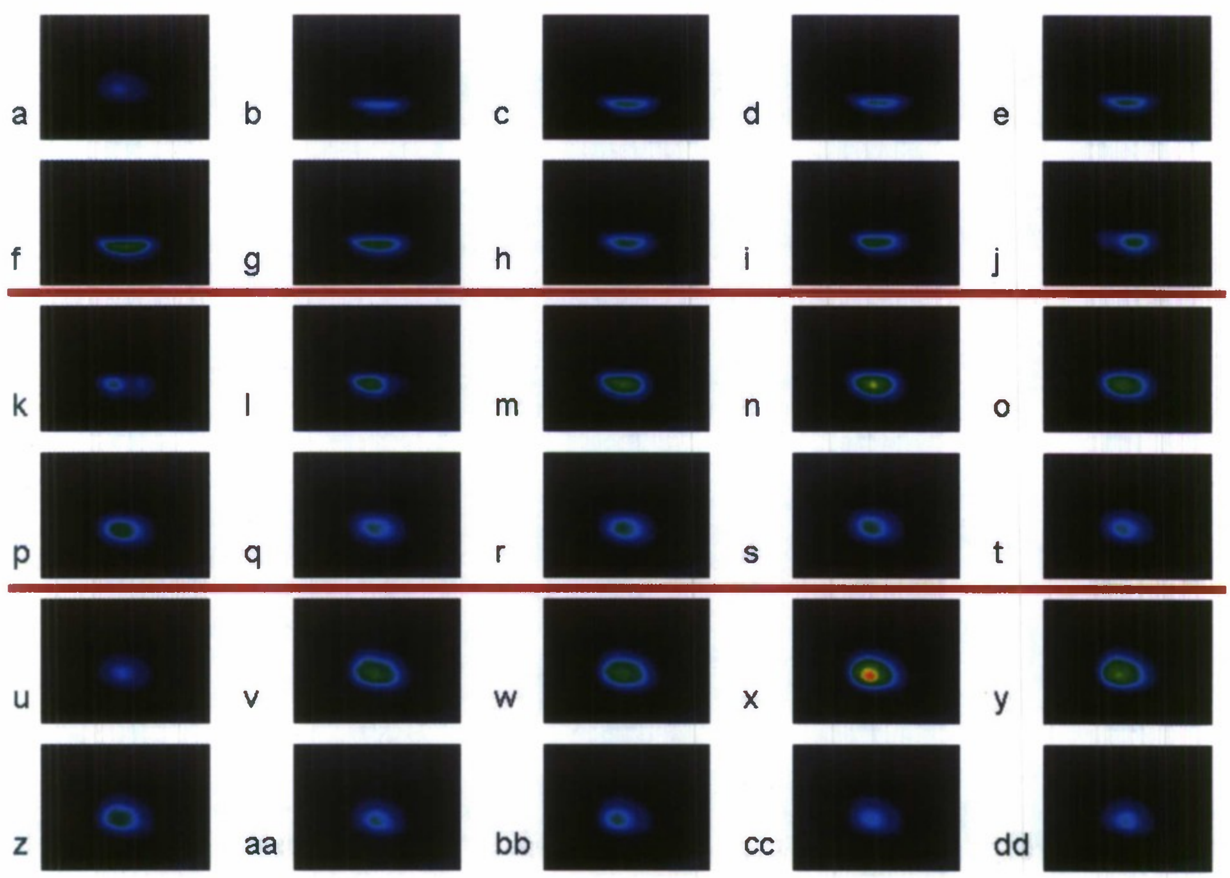

Fig. 5. Images of the pump beam profile from the ~2 μm optical parametric oscillator (OPO) output. The OPO operates at 10 Hz, while the camera repetition rate is 30 Hz.

mid-IR affords a combined examination of the spatiotemporal behavior of the laser light. In the thirty images shown in Fig. 5, the camera is run at an arbitrary phase relative to the 10 Hz pulsed pump beam. This offers an opportunity to examine the variation of the beam shape as a function of time through three duty cycles of the pump laser. Details to notice in the images are both the similarities and differences of the beam shape at nearly identical phases of the beam cycle. Examples are images **(a)**, **(k)**, and **(u)** as well as images **(d)**, **(n)** and **(x)**.

Analysis continues on earlier OPIC work from data gathered while at the University of Kansas. A manuscript is in preparation reporting on a cavity length study in which OPIC lasers prepared at Sarnoff Corporation demonstrated a transparency pump intensity characteristic temperature ~56 K (Fig. 6) and low internal losses, ~1-2 cm^{-1} at 78 K and ~12 cm^{-1} at 200 K (Fig. 7). This work will be submitted to *Journal of Applied Physics*.

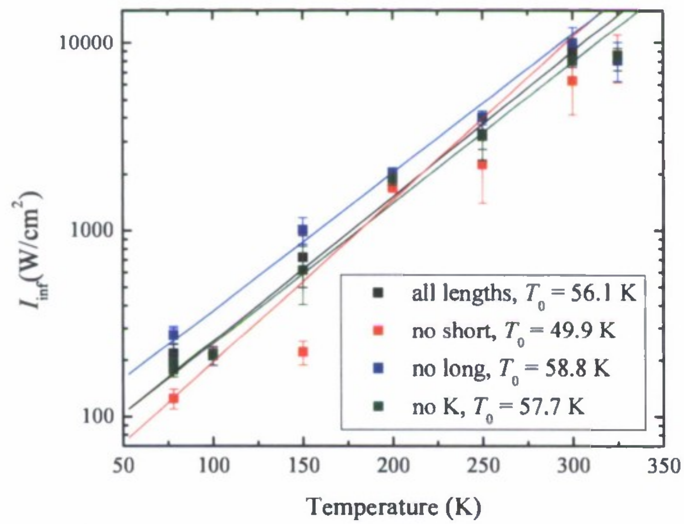

Fig. 6. Transparency pump intensity *vs*. temperature. Transparency pump intensity values are shown for several fitting conditions and yield consistent transparency characteristic temperatures, as determined by exponential growth fits.

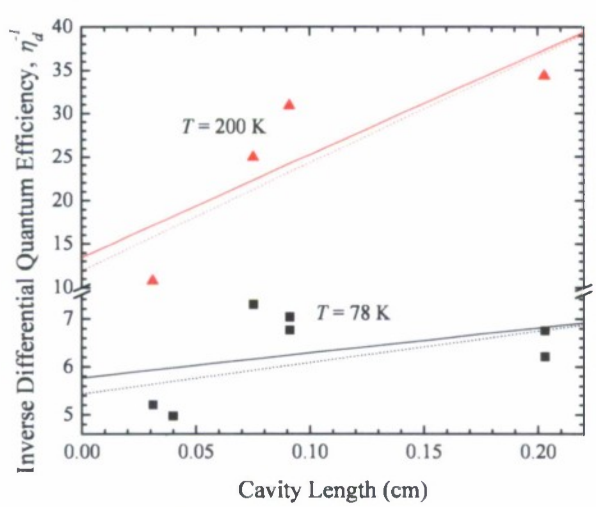

Fig. 7. Inverse differential quantum efficiency vs. cavity length at 78 K (black squares) and 200 K (red triangles). Solid lines are fits including all cavity lengths, while the dashed lines are fits that exclude the 753 μm cavity.

Nordheden at University of Kansas:

Laser definition in previous work was done with wet etching. It is anticipated that the plasma definition of the structures will improve device performance. The etch studies were performed in the Oxford Instruments System 100 ICP 180 described above in the ZnO etch study section. ICP etching is preferable to RIE because of the indium content on the surface of the device epitaxial layers. Typically with RIE one has to wet etch through the indium containing cap layer and then plasma etch through the remaining layers. With ICP the entire layer structure can be etched.

Initial etch studies were performed on some existing epitaxial PHEMT material that we had on hand to demonstrate the ability to etch through indium containing surface layers (like the mid-IR structures). The existing material had a 750Å GaAs cap layer over an underlying InGaP layer. The GaAs cap layer was selectively wet etched using a 1:8:640 solution of H_2SO_4:H_2O_2:H_2O with an etch rate near 7.5 Å /sec. The samples were then patterned with S1818 photoresist as a mask and etched in a mixture of BCl_3/Ar at a pressure of 15 mTorr, 400W ICP, and 100W RF power. The results for the HEMT material and two samples of GaSb are shown in Figure 8 as a function of the percentage of BCl_3. Further etch development with a lower RF bias and the addition of helium backside cooling was investigated to help improve the photoresist selectivity and removal. A final etch process for the anitmonide laser structure definition was determined to be a 25% BCl_3 in argon mixture (5 sccm BCl_3 and 15 sccm argon), with an ICP power of 400W, an RF power of 70W, 10 Torr helium pressure, with a resulting etch rate of 300 nm/min. Laser structures will be etched and then sent in the next month to Dr. Olafsen at Baylor for characterization.

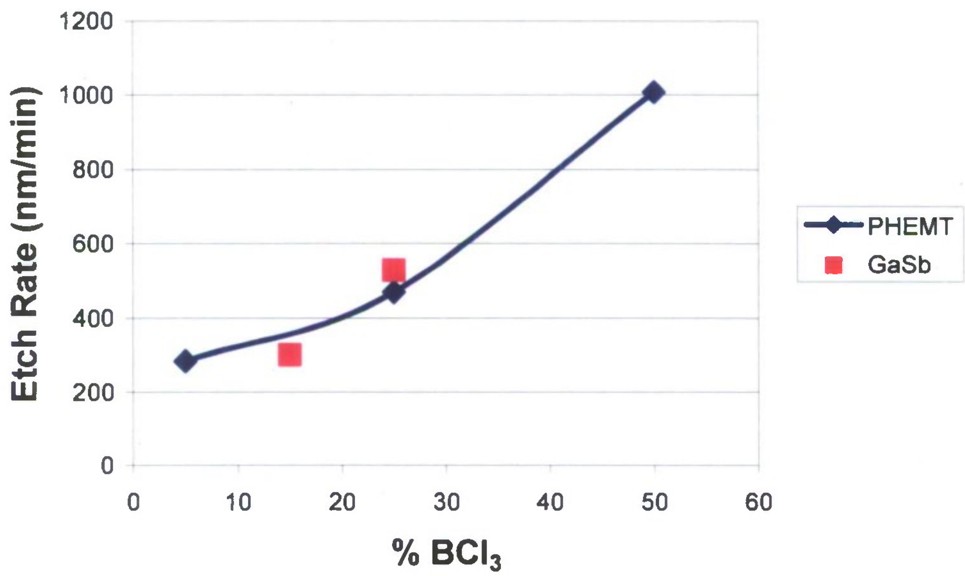

Fig. 8 Etch rate as a function of %BCl_3 in BCl_3/Ar mixtures for PHEMT and GaSb layers (15 mTorr, 20 sccm, 400W ICP, 100W RF).

Equipment installation and purchases:

Installation of the new Oxford ICP (Inductively Coupled Plasma) etching and PECVD (Plasma Enhanced Chemical Vapor Deposition) systems (purchased by the University of Kansas) was completed in June 2008. Since then we have characterized plasma etch chemistries for the definition of the antimonide laser structures with ICP etching and also their passivation with silicon nitride using the PECVD system. The ICP etching system has also been used to develop etch chemistries for ZnO etching.

A new Horiba Jobin Yvon Uvisel high accuracy spectroscopic ellipsometer was purchased ($116K) with the matching funds from KTEC at the end of 2007 and was installed in May 2008 in the Multidisciplinary Research Building (MRB) cleanroom. A representative came out to train users on the instrument. The ellipsometer is capable of not only measuring simple thin film thicknesses of materials such as photoresist, nitrides and oxides on substrates, but can be programmed for more complex layer structures such as the heterostructures used for the antimonide lasers.

Matching funds from KUCR ($15K) were used to contribute to the purchase of a new ABM mask aligner that is located in the MRB cleanroom (so we won't have to drive across campus to use the aligner in Physics), and the remaining matching funds from Physics & Astronomy were used to purchase a Nikon 1000X optical microscope. The turbo pump for the RIE system was purchased in 2007, and has been installed on the Plasma Therm system.

Personnel supported:	Karen J. Nordheden,	Associate Professor
	Mike Santilli,	PhD student and then Post Doctoral Research Assistant (now at the Stowers Institute—as of September 2007)
	Bogdan Pathak,	Graduate Research Assistant (completed MS August 2008)

(graduate students supported by Linda Olafsen when she was PI have both graduated with their Ph.Ds. Mike Santilli was one of those students and he finished in December 2006)

Publications:

Karen J. Nordheden, Bogdan A. Pathak, and John L. Alexander, "ICP Etching of ZnO in BCl_3/SF_6 gas mixtures," to be published in the Proceedings of the SPIE, Photonics West, SPIE Vol. 7217, 2009. (Invited)

Karen J. Nordheden, Mark Dineen, and Colin Welch, "Inductively coupled plasma etching of ZnO," Proceedings of the SPIE, Photonics West, SPIE Vol. 6474, pp. 6474OP1-4, 2007. (Invited)

Michael R. Santilli, "Cavity length study of an electrically pumped W-Well Laser," Ph.D. Dissertation, University of Kansas, 2006.

Interactions:

We continue to collaborate with Linda Olafsen at Baylor University. We have developed a plasma etch process using BCl_3/Ar gas mixtures to define the antimonide-based heterostructure laser devices. Optical and electronic measurements of these processed materials will be performed by Linda Olafsen at Baylor. We have also continued to collaborate with Nanovation SARL (France) for the ZnO etching.

New discoveries, inventions, or patent disclosures: None

Honors/Awards: None

Other:

Equipment on loan to Linda Olafsen:

1) Optical Spectrometer---still on loan for optical testing
2) Cryostat & Temperature controlled sample enclosure with windows for optical measurement---returned
3) Oscilloscope---returned

*****This was submitted last year but I asked to send a follow up report*****

AFOSR Final Performance Report, March 2008

Award No.: FA9550-04-1-0433

Title: High Efficiency, Room Temperature Mid-Infrared Semiconductor Laser Development for IR Countermeasures (DEPSCoR)

Principal Investigator: Karen J. Nordheden (replacement PI for Linda Olafsen)

Institution: University of Kansas Center for Research, Inc.
2385 Irving Hill Rd.
Lawrence, KS 66045-7563

Revised Objectives:

There will be no major changes to the overall original grant proposal objectives which include the optical and electronic characterization and fabrication of antimonide-based semiconductor lasers for infrared applications. The fabrication of the devices will continue to be done at KU (Nordheden), and the optical and electronic characterization of the devices will be carried out at Baylor (Olafsen, without the use of any DEPSCoR funds). The necessary fabrication equipment for photolithography, metallization, plasma etching and passivation will all remain at KU. The KTEC equipment matching funds which remain unspent will be used to purchase a thin film measurement system. The optical and electronic characterization equipment will move to Baylor. Dr. Nordheden will develop plasma processes for antimonide-based semiconductor etching and nitride passivation. Since the same supplies/equipment which will be used for etching the antimonide materials can also be used for ZnO etching, we plan to expand the original work to include this as well.

Revised Budget:

The equipment match from the State of Kansas (KTEC) will be used to purchase a thin film/index of refraction measurement system (either an ellipsometer or NanoSpec 3000) to help monitor thin films during processing (nitride and/or photoresist thicknesses, etc.). The remaining equipment funds will be used to purchase a turbo pump for the RIE system and a 1000X optical microscope for process inspection.

STATUS OF EFFORT:

The status of effort section will be divided into three categories: ZnO etching results, mid-IR antimonide laser progress, and equipment installation and purchases.

ZnO etching results:

Since taking over the grant in September 2006, initial studies of plasma etching of ZnO have been accomplished. These studies were done in collaboration with Mark Dineen and Colin Welch at Oxford Instruments since our system was not yet online. The etch studies were performed in Oxford ICP 180 and 380 systems at Oxford Instruments. Samples were etched in CH_4/H_2 and $BCl_3/CH_4/H_2$ gas mixtures. At 2500 W ICP power, 50/15 sccm CH_4/H_2, and 250 W RF bias power, an etch rate of 112 nm/min was achieved. This rate is comparable to the etch rates reported by others under similar conditions. A cross-section of this sample is shown in Figure 1. The photoresist mask is still in place. The surface is smooth and the profile is anisotropic with a sidewall angle of about 83 degrees. The sidewall angle is strongly dependent on the initial photoresist mask profile. Due to the propensity of CH_4/H_2 gas mixtures to form polymer compounds, the chamber needed to be cleaned periodically in SF_6/O_2.

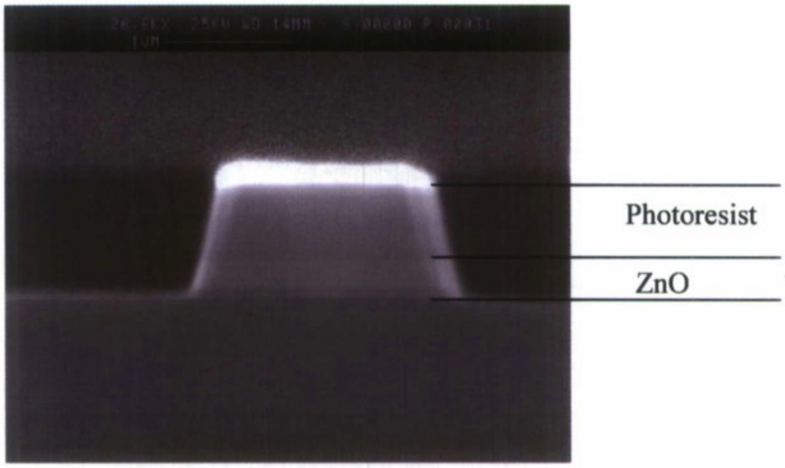

Fig. 1. Cross-section of ZnO etched in CH_4/H_2 (10 mTorr, 50/15 sccm CH_4/H_2, 2500 W ICP power, 250 W RF bias power).

The etch rate of ZnO in a 20/20/20 sccm mixture of $BCl_3/CH_4/H_2$ at a pressure of 10 mTorr and an ICP power of 700 W is shown in Figure 2 as a function of RF bias power. These samples were grown by Nanovation SARL (France). The etch rate increased from 46 nm/min at 300 W RF bias to 211 nm/min at 400 W RF bias power. The etch time for these samples was only one

minute so they were too shallow to observe etch profiles. Once again these rates are consistent with those reported in the literature under similar conditions.

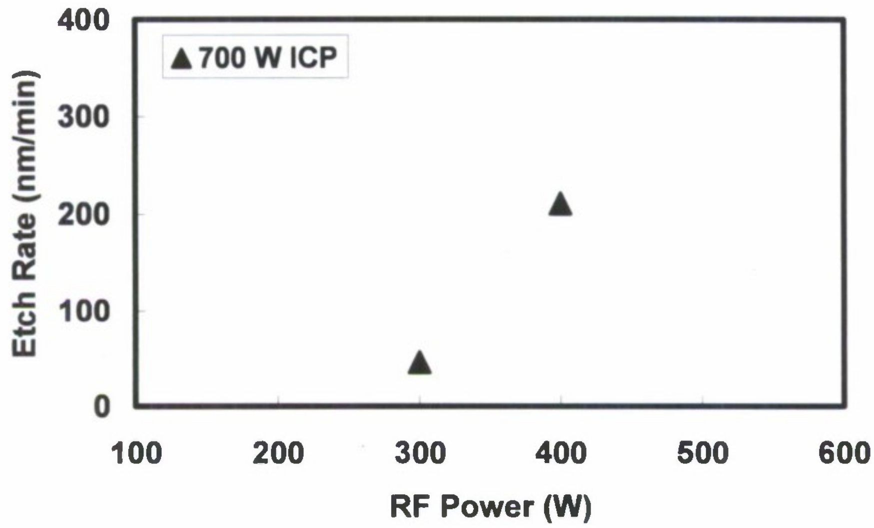

Fig 2. ZnO etch rate in $BCl_3/CH_4/H_2$ as a function of RF bias power (10 mTorr, 20/20/20 sccm $BCl_3/CH_4/H_2$ and 700 W ICP power).

ICP etching of ZnO in C_2F_6 and NF_3 plasmas with etch rates near 400 nm/min, with smooth surfaces and reasonably vertical sidewalls were recently reported. One might expect the etch rate in fluorinated gases to be lower than in chlorinated gases due to the differences in the vapor pressures of possible etch products such as zinc fluoride and zinc chloride (7.5 mTorr or 1 Pa at a temperature of 731°C and 305°C respectively), however, these rates are higher than the fastest etch rates reported in either $CH_4/H_2/Ar$ plasmas (300 nm/min), or $BCl_3/CH_4/H_2$ plasmas (310 nm/min). Future work in ZnO etching will include experiments in fluorinated gases. We will also continue to collaborate with Ferechteh Teherani and David Rogers of Nanovation SARL (France).

Mid-IR Antimonide laser progress:

Olafsen at Baylor:

It has taken some time for Linda Olafsen's new laboratory at Baylor to be set up to the point where she could unpack and get everything set up. Her new lab is coming along well now. Since the May report, progress has been made on both the optical and electrical pumping fronts. Dr. Daniel Mixson (Assistant Professor at the Naval Academy Preparatory School in Newport, RI) completed a summer project as part of the Research Experience for Teachers program at Baylor. His work focused on establishing the electrical pumping set-up, including AVTECH current pulser and boxcar/gated integrator. He used the electrical set-up to measure current-

voltage (I-V) characteristics of several infrared LEDs, including a type-II W-well laser grown by Molecular Beam Epitaxy at Naval Research Laboratory. We have also looked at the mid-IR output from this laser (~3 μm) using both a photovoltaic indium antimonide detector and an IR camera from Electrophysics, Inc. This academic year, University Scholar Windrik Lynch is measuring beam profiles from this laser using a variety of methods (IR camera vs. blade, slit, or pinhole into InSb detector) to better understand the shape of the output beam and to decouple that shape from the different measurement methods and inherent experimental artifacts due to measurement limitations.

New Ph.D. student Angela Douglass has been working with the Nd:YAG laser and optical parametric oscillator and has been aligning optics and assembling instrumentation for optical pumping. She will first investigate W-well optical pumping injection cavity (W-OPIC) lasers, and will move to optical pumping/modulation of the electrically injected lasers. We are also working with Spectra-Physics, the manufacturer of the Nd:YAG/OPO system to increase output powers so that optical pumping may be effectively achieved beyond 2 μm.

A Varian FTS-7000 step-scan Fourier Tranform Infrared Spectrometer has been installed, and in addition to measuring reflectivity curves from the surface of W-OPIC lasers, we continue to work on coupling the light output from both optically and electrically pumped lasers into the spectrometer for high-resolution emission spectra.

Nordheden at University of Kansas:

Here at KU, we are preparing some existing epitaxial material that we had on hand to demonstrate the ability to ICP etch through indium containing surface layers (like the mid-IR structures). The existing material has a 750Å GaAs cap layer over an underlying InGaP layer. We have etched through the GaAs cap layer using a 1:8:640 wet etch solution of H_2SO_4:H_2O_2:H_2O with an etch rate near 7.5 Å /sec. Linda Olafsen has sent us the relevant mask so we can have these samples prepared and waiting when the ICP is brought online. Our intent is to practice on these samples and then use the developed etch recipe on the actual device structures. ICP etching is preferable to RIE because of the indium content on the surface of the device epitaxial layers. Typically with RIE one has to wet etch through the indium containing cap layer and then plasma etch through the remaining layers. With ICP the entire layer structure can be etched.

Equipment installation and purchases:

Installation of the new Oxford ICP (Inductively Coupled Plasma) etching and PECVD (Plasma Enhanced Chemical Vapor Deposition) systems has progressed more slowly than anticipated. After multiple delays with the contractor (some due to KUCR withholding payment and misunderstandings of the content of original work order, and some due to incorrect installation of the exhaust lines leading to inadequate exhaust flow), we are close to bringing the two systems online. The only missing part is a valve for the new larger diameter exhaust line which should be here within the week. Matheson has already been out to do the training and final installation of the compressed gas cabinets and Oxford is scheduled to come out and bring the two plasma systems online on or around October 1. Once these systems are operational we will be able to

define the antimonide laser structures with ICP etching and also be able to passivate the structures. Mike Santilli (former PhD student under Linda Olafsen) finished writing and depositing his Ph.D. in December 2006 and was a Post-Doctoral research assistant over the past year. He helped to oversee the installation of the new equipment with Bogdan Pathak (graduate research assistant). Mike Santilli has recently accepted a job at the Stowers Institute in Kansas City, MO.

A new Horiba Jobin Yvon Uvisel high accuracy spectroscopic ellipsometer was purchased ($116K) with the matching funds from KTEC at the end of last year and was installed this May in the Multidisciplinary Research Building (MRB) cleanroom. A representative came out to train users on the instrument. The ellipsometer is capable of not only measuring simple thin film thicknesses of materials such as photoresist, nitrides and oxides on substrates, but can be programmed for more complex layer structures such as the heterostructures used for the antimonide lasers.

Matching funds from KUCR ($15K) were used to contribute to the purchase of a new ABM mask aligner that is located in the MRB cleanroom (so we won't have to drive across campus to use the aligner in Physics), and the remaining matching funds from Physics & Astronomy will be used to purchase a 1000X optical microscope (DONE). The turbo pump for the RIE system was purchased last year.

Personnel supported: Karen J. Nordheden, Associate Professor
Mike Santilli, Post Doctoral Research Assistant (now at the Stowers Institute—September 2007)
Bogdan Pathak, Graduate Research Assistant

(graduate students supported by Linda Olafsen when she was PI have both graduated with their Ph.Ds. Mike Santilli was one of those students and he finished in December 2006)

Publications:

Karen J. Nordheden, Mark Dineen, and Colin Welch, "Inductively coupled plasma etching of ZnO," Proceedings of the SPIE, Photonics West, SPIE Vol. 6474, pp. 6474OP1-4, 2007. (Invited)

Interactions:

In the coming months, with the ICP, PECVD, and Horiba UVISEL ellipsometer systems installed in the new Multidisciplinary Research Building at KU, plasma etching and other fabrication of antimonide-based heterostructure devices will be accomplished on site, while optical and electronic measurements of these processed materials will be performed by Linda Olafsen at Baylor University. We will also continue to collaborate with Nanovation SARL (France) for the ZnO etching.

New discoveries, inventions, or patent disclosures: None

Honors/Awards: None

Other:

Equipment on loan to Linda Olafsen:

1) Optical Spectrometer
2) Cryostat & Temperature controlled sample enclosure with windows for optical measurement
3) Oscilloscope

I originally requested the return of the equipment in September 2007, but we will extend this deadline to April 2007 to accommodate the 6 month no cost extension of the grant.

*****Below is Linda Olafsen's Final Report from 2006.*

AFOSR Performance Report, September 1, 2005–August 25, 2006

Principal Investigator: Linda J. Olafsen

Institution: University of Kansas Center for Research, Inc.
2385 Irving Hill Rd.
Lawrence, KS 66045-7563

Award No.: FA9550-04-1-0433

Objectives: No change from proposal.

Status of effort: In the second year of the project, optical pumping research continued and electrical injection measurements were added to the effort to improve data acquisition for meeting the objectives toward mid-infrared semiconductor laser investigation and development.

After completing a cavity length study of an optical pumping injection cavity laser structure grown at Sarnoff Corporation in collaboration with Naval Research Laboratory in Washington, DC, graduate student Todd McAlpine analyzed this data and presented it in his thesis dissertation. The optical pumping injection cavity lasers, in which the active region of the antimonide-based semiconductor is sandwiched between two distributed Bragg reflectors tuned to the pump wavelength in order to cause multiple passes of the pump photons, increasing absorption and thereby efficiency, demonstrated room-temperature emission at 3.2 μm. He measured light-light curves for five different cavity lengths and obtained internal loss coefficients, external differential quantum efficiencies, and thresholds comparable to previous results in other structures. The results indicated that further design work is needed (in collaboration with experts in computation and theory) to decrease intervalence band absorption in these mid-IR devices. One very favorable characteristic was the above-room temperature operation of these lasers at low duty cycles.

Kristina Young completed a Master's project performing a computational analysis of the temperature dependence of the resonant pump wavelength. While originally believed that the temperature variation in the resonance pump wavelength would purely or dominantly be a thermal expansion effect due to the lattice constant variation with temperature in the Bragg mirrors used to create the resonant cavity, Kristina's models indicate that the dominant effect is in fact the temperature dependence of the refractive index.

With regard to moving toward optimized electrical pumping, graduate student Michael Santilli began constructing an experiment in which there will be dual pumping. Laser devices will be fabricated and isolated as individual mesas. Metal stripes will be applied on the lateral edges and the heterostructures will be optically pumped in the middle. Michael and Kristina designed photomasks for this effort, and Todd and Michael wrote LabVIEW programs for the data acquisition. By examining the light-current curves as a function of optical pumping wavelength, it will be possible to construct new information about the energy level structure and electric fields internal to these devices. This information will help to optimize future device design and performance. Faulty equipment on the Nd:YAG laser used to pump the OPO and provide the variable wavelength pumping slowed this effort, which will be resumed at Baylor University in the coming year.

Fabrication aspects of the project will continue at KU under the supervision of Prof. Karen Nordheden in Chemical and Petroleum Engineering, with particular focus on ICP etching of antimonide-based materials for laser fabrication.

Accomplishments: Full analysis of the first cavity length study using a variable pump wavelength technique was completed by Todd McAlpine, who successfully defended his doctoral dissertation. The W-OPIC's worked at higher temperatures than lasers utilizing the

Integrated Absorber configuration. Losses and thresholds were comparable to other W-devices. This work's primarily accomplishment is demonstration of the viability of the variable/resonant pump wavelength technique for optical injection of carriers in semiconductor lasers.

In addition, graduate student Michael Santilli performed electrical injection experiments and a corresponding cavity length study in an effort to move toward a hybrid experiment in which optical pumping will be performed on electrically injected devices in order to measure enhancements (or detriments) to threshold current densities and power conversion efficiencies for these devices. This technique will help uncover the underlying physics in these materials.

The (solely) electrical injection experiments yielded only modest external differential quantum efficiencies (<1%), but provided a good test run in preparation for the study of samples more tailored to the hybrid optical/electrical experiment.

Personnel supported: Linda J. Olafsen, Associate Professor
Todd C. McAlpine, Graduate Research Assistant
Kristina G. Young, Graduate Research Assistant

Publications: Todd C. McAlpine, "Cavity Length Study of a Resonantly Pumped W-OPIC Semiconductor Laser," Ph.D. Dissertation, University of Kansas, 2006.

Michael R. Santilli, "Cavity length study of an electrically pumped W-Well Laser," Ph.D. Dissertation, University of Kansas, 2006.

Kristina G. Young, "Resonant Pump Wavelength Variation in an Optical Pumping Injection Cavity Laser," Master's Thesis, University of Kansas, 2006.

Progress in Semiconductor Materials V -- Novel Materials and Electronic and Optoelectronic Applications, edited by **Linda J. Olafsen**, Robert M. Biefeld, Michael C. Wanke, Adam W. Saxler (Mater. Res. Soc. Symp. Proc. **891**, Warrendale, PA, 2006).

Several publications will derive from these students' work in the coming year.

Interactions: We continued work with Professor Karen Nordheden in Chemical and Petroleum Engineering who was previously supported by a separate DEPSCoR award and will be assuming the role as PI on this grant with Professor Linda Olafsen's transfer to Baylor University. In the coming year, with ICP and PECVD systems recently installed in the new Multidisciplinary Research Building at KU, plasma etching and other fabrication of antimonide-based heterostructure devices will be accomplished on site, while optical and electronic measurements of these processed materials will be performed at Baylor University. The new equipment described above will enhance that effort and Professors Nordheden and Olafsen should enjoy a fruitful collaboration.

New discoveries, inventions, or patent disclosures: None

Honors/Awards: None